Simulation-driven design optimisation of instrument panel to improve upper leg injury of occupant in truck collision

Prathamesh M. Dehadray, K. Vineeth Kumar Reddy

Abstract Commercial vehicle safety has been gaining importance in recent times in response to the substantial increase in the number of truck occupants involved in crash impacts. Euro NCAP has extended the scope of vehicle safety to include safety for commercial vehicles. As per the statistical data presented by Euro NCAP, between 2017 and 2019, 11.7% of fatalities resulted from collisions involving heavy duty trucks. It is therefore necessary to focus attention on the safety of heavy-duty truck occupants. Restraint systems like airbags and seatbelts with pretensioners play a vital role in safeguarding the occupant during a collision. Fatal injuries in trucks can be controlled using airbags and seatbelt systems and by tuning them for optimised head and chest injury performance, which are crucial for occupant survival. However, controlling the lower extremity injuries in a truck environment is equally important because, unlike passenger car interiors, the truck occupants will interact with stiff interior parts. The present study deals with controlling driver knee and femur injuries in frontal truck-to-truck collisions in cab-over-engine trucks by optimising the instrument panel design. THOR (Test Device for Human Occupant Restraint) finite element dummy models are used for simulating the crash scenario in the LS-DYNA environment.

Keywords Design optimisation, finite element analysis, heavy-duty trucks, interior safety, knee and femur injuries.

I. INTRODUCTION

Automobiles are classified based on their nature, load-carrying capacity, functionality, design, fuel used, number of wheels, etc. All heavy-duty vehicles fall under the category of goods vehicles. Modern trucks are available in a variety of models. They differ in type of body cabin, length and number of axles. Trucks are classified by the Gross Vehicle Weight Rating (GVWR) system. Trucks with a GVWR greater than 26,000 lbs (11,793 kgs) are considered heavy-duty trucks. Road traffic safety has become a major area of research over the past few decades. There is a high fatality rate in several types of vehicle accident, hence a great deal of effort has been put into research and development of vehicles to make them safer. Heavy-duty trucks are more prone to fatal crashes, albeit they account for a significantly lower percentage of road users than passenger vehicles. John Woodrooffe and Daniel Blower concluded that frontal collision and rollover accidents cause 72.7% of driver fatalities out of all types of truck-tractor accidents [1].

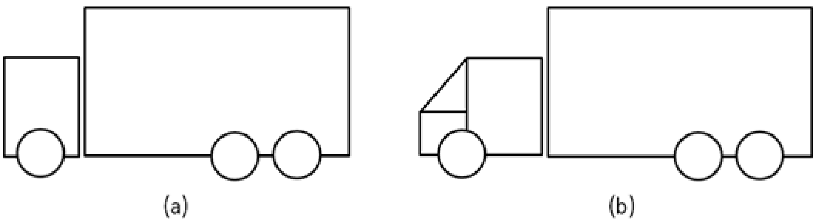

Fig. 1. (a) Cab-over-engine truck. (b) Conventional truck.

Heavy-duty truck cabins are categorized as conventional or cab-over-engine (COE). The typical schematic of each cabin type is shown in Fig. 1. Conventional trucks have a separate hood in the front and the cab is placed behind the engine. These trucks have better crash performance due to their longer hood, which acts as a crumple

P. Dehadray (tel: 8605035762; e-mail: prathamesh.dehadray@volvo.com) is occupant safety analyst and V. Reddy is specialist occupant safety analyst at Volvo Group Trucks Technology in India.

zone in frontal impact, absorbing impact energy and thereby protecting the occupant. In cab-over-engine trucks, the cab is mounted directly over the engine, which means a shorter overall length that is beneficial for maneuvering in urban areas. However, occupants are exposed to higher risk of injury as these trucks do not have a crumple zone. The present study deals with occupant injury performance in a cab-over-engine truck impacting a barrier which represents real accident scenario of truck impacting the trailer from behind.

Vehicle interior plays a crucial role in controlling leg injuries when a vehicle is subjected to frontal crash. The use of knee airbags, knee bolsters and lap pretensioners can reduce knee injuries. Stiffness of the dashboard also plays a crucial role in controlling knee injuries [2]. The area where the knee impacts the dashboard should have higher stiffness, while the area where the upper tibia impacts the dashboard should have lower stiffness. Using a case study, Gokhale *et al*. developed and validated the process for optimising knee bolsters to reduce upper leg injury. They evaluated many proposals and developed metallic bolsters based on material, packaging, cost, and weight constraints. Subsystem level simulations were performed using LS-DYNA and validated through experimental testing [3]. Ahmed and Patra evaluated occupant injury levels for different combinations of restraint systems in heavy-duty trucks. A Hybrid III 50th percentile ellipsoid dummy was used for the analysis, and the steering column, dashboard, roof and seat were modelled as heavy-duty truck environment. Their study concluded that the use of seat belt and airbag reduced the occupant head, neck and chest injuries when compared to an impact scenario without restraint systems [4]. According to the analysis made using data from NASS/CDS, the risk of lower limb injuries was found to be significantly higher than the risk of upper extremity injuries in all modes of crash events. Though lower limb injuries are not fatal, they can cause permanent disability and impairment. More than 50% of AIS2+ injuries are associated with Knee-Thigh-Hip (KTH) injury, which leads to 42% of corresponding life years lost to injuries [5]. Mahesh, Chouhan *et al*. evaluated the use of knee airbag to reduce knee injuries in a passenger car during a frontal collision. According to a research report studied by authors, knee injury accounts for more than 30% of lower limb injuries [6]. The performance of the knee airbag was analysed using the finite element (FE) method and a Hybrid III 50th percentile dummy in a sled environment. The use of knee airbag was found to reduce femur forces by 68%.

II. METHODS

Much effort has been focused on improving rates of upper leg injury in frontal crashes for passenger cars, but limited work has been carried out to investigate and improve rates of leg injury in heavy-duty trucks. The most common accident type of commercial vehicles is collision with another truck going in the same direction, which accounts for 15–20% of fatalities of total accidents. Figure 2 represents the typical full-frontal trailer back-load case that is commonly used to evaluate the crash performance of trucks. The barriers represent the rear end of the trailer and truck being impacted at a relative velocity between the trucks. The load case simulated is derived from real-time collision scenarios, which can be anticipated as a prominent load case in truck safety in Euro NCAP's vision for safer trucks in future years [7].

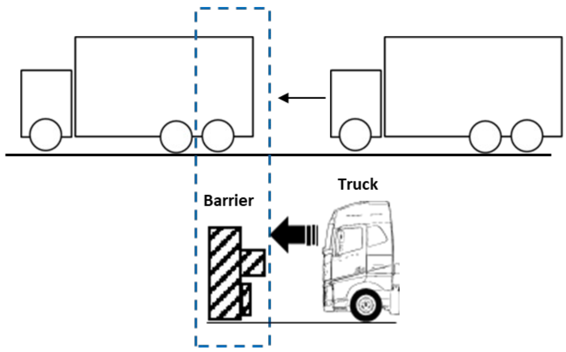

Fig. 2. Load-case details.

A detailed FE model of a full vehicle truck with interior system was created and simulated in LS-DYNA solver, with the THOR-50M dummy used to evaluate driver injury performance [8]. The process was then iteratively refined to achieve optimum contour and stiffness of instrument panel, which resulted in improving knee shear displacement and femur compression forces.

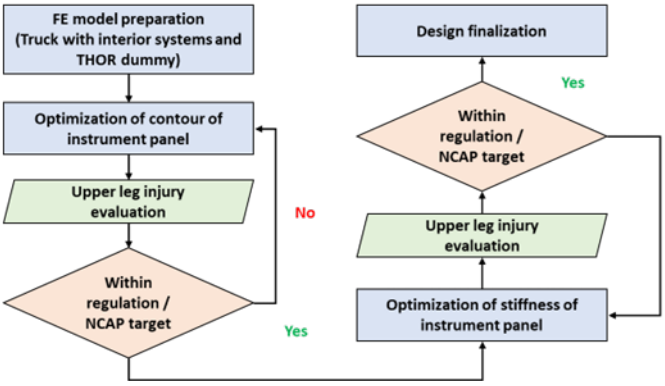

Fig. 3. Methodology.

Knee injuries are the most common type of lower extremity injuries in frontal crash accidents of trucks. They typically occur due to direct impacts or extreme forces acting on the knee joint. During a frontal crash event, the knees of the occupant collide with various vehicle interior systems, such as the instrument panel or steering shroud, resulting in injury to the knee. The type of knee injury sustained will depend on the position of the occupant's legs, firewall intrusion, design and stiffness of instrument panel [2]. During accident or sudden deceleration, lower-body parts experience significant forces. Knee shear displacement occurs when movement of the tibia is restricted due to stiff dashboard near the upper tibia zone. Knee shear displacement or knee slider can result in various types of injury, including knee fractures, joint dislocation, meniscus injuries and ligament tears. Excessive knee slider can tear ACL (Anterior Cruciate Ligament) and PCL (Posterior Cruciate Ligament).

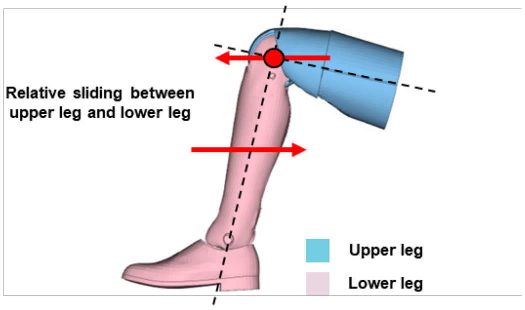

Fig. 4. Knee shear displacement.

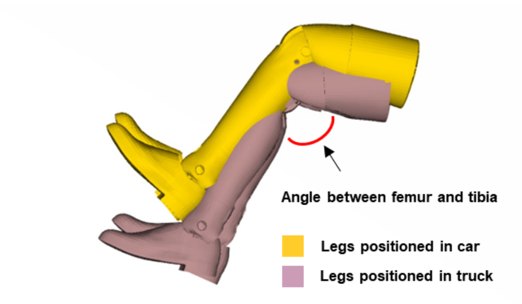

Fig. 5. Position of legs in passenger cars vs trucks with same H-point.

The position of occupant legs in passenger cars and trucks varies due to differences in cabin design, space, size, seating arrangements and driving ergonomics. In passenger cars, the occupant seat is positioned relatively low as compared to trucks. This lowered seating position results in extended knee angle, allowing the driver to reach the pedals comfortably. Trucks often have a higher ground clearance and higher seating position, which offers better visibility for the driver. The higher seating position in trucks results in a lower angle between femur and lower leg. Figure 5 shows the comparison of leg position between passenger cars and trucks.

III. RESULTS

Contour of instrument panel

The contour of the instrument panel has a significant impact on occupant knee injury during a collision. An instrument panel with inappropriate or poorly designed contours can increase the risk of knee injuries, while a well-designed panel can help to mitigate the severity of knee injuries. The angle of the panel design with respect to vertical (α) should be optimised for occupant upper leg injury performance, as shown in Fig. 6.

Baseline contour (Contour A) of instrument panel and impact position of occupant legs are shown in Fig. 6. It is observed that the tibia impacts first with instrument panel, before the knee, during frontal collision. This allows the knee to slide towards the instrument panel, resulting in negative knee shear displacement. This will lead to ligament tear (ACL and PCL) between knee and tibia.

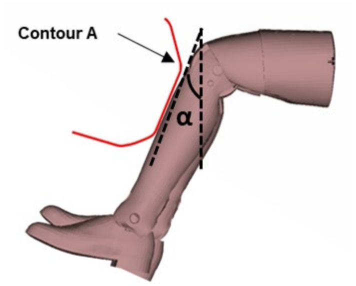

Fig. 6. Impact position of leg with respect to Contour A.

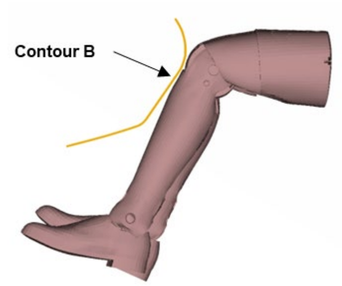

Fig. 7. Impact position of leg with respect to Contour B.

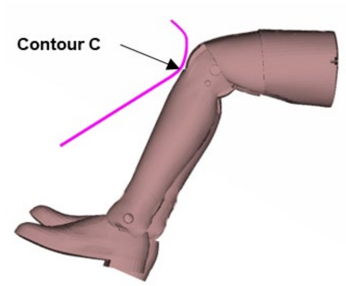

Fig. 8. Impact position of leg with respect to Contour C.

Considering the drawbacks of Contour A on the knee shear displacement, Contour B is designed in such a way that knee and tibia collide at the same time with the instrument panel, as shown in Fig. 7. Knee shear displacement with Contour B has shown improvement when compared with Contour A. However, it is observed that knee shear injury can be improved further by fine-tuning the angle and contour of the instrument panel. Applying the lessons learned from previous designs, the contour of the instrument panel was designed in such a way that the knee would have first point of contact with the instrument panel, as shown in Fig. 8. This design has further reduced the knee shear displacement injury, as shown in Fig. 9.

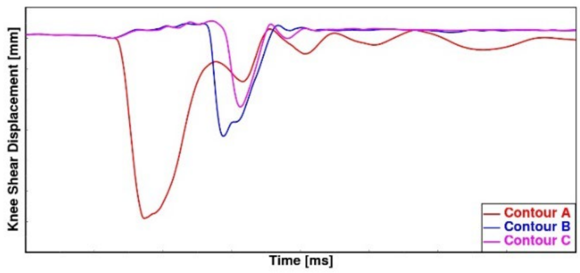

Fig. 9. Effect of instrument panel contour on knee shear displacement.

Stiffness of instrument panel

The stiffness of the instrument panels also plays a crucial role in mitigating knee injuries in frontal collisions. A dashboard with adequate stiffness can absorb and dissipate some impact energy during collision. The dashboard should deform to absorb the energy of the impact, reducing the forces transmitted to the knees. The gradual energy absorption helps to slow down the deceleration of knees, thus reducing the severity of knee injury.

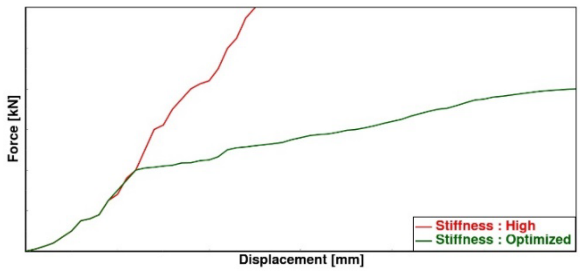

Fig. 10. Force [kN] vs Displacement [mm].

By having softer or deformable zones, the force is spread over a wider area, minimising concentrated stress on the knees. The typical schematic representation of force distribution to optimise the stiffness of instrument panel is shown in Fig. 10. In the initial concept, all stiff electrical systems were packaged in the tibia impact zone, which restricted the movement of the tibia, resulting in higher knee shear displacement. Ensuring proper packaging of instrument panel plays a crucial role in overall stiffness. The knee impact zone in instrument panel should be optimised in such a way that it offers sufficient resistance to the knee during the collision as well as maintaining the femur compression force within limits. Lower stiffness of instrument panel at tibia impact zone allows gradual loading of tibia on instrument panel, which helps to reduce the knee shear displacement, as shown in Fig. 11. The improved contour and stiffness optimisation of instrument panel also improves the femur compression force, as shown in Fig. 12.

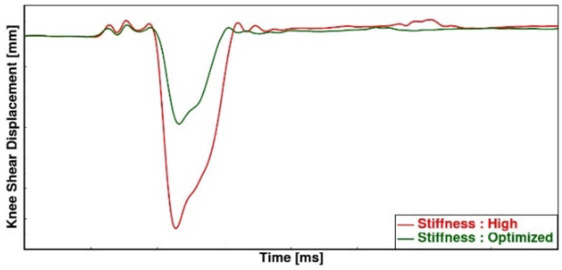

Fig. 11. Effect of stiffness on knee shear displacement.

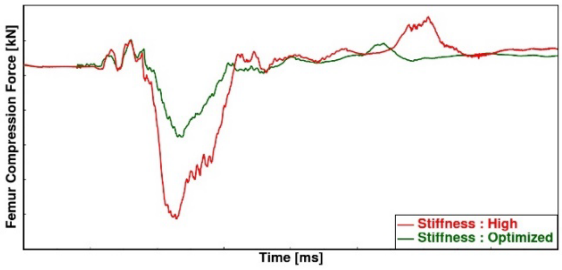

Fig. 12. Effect of stiffness on femur compression force.

IV. DISCUSSION

From the present study, it is observed that upper leg injury can be controlled by simulation-driven instrument panel design, involving the panel angles as well as the stiffness of overall instrument panel assembly. Unlike passenger cars, the occupant's H-point (seating position) in trucks is comparatively higher, resulting in a tibia angle that is close to perpendicular with respect to the floor. This position of the occupant makes it important to design the instrument panel contour in such a way that the tibia should not contact the instrument panel before the knees.

V. CONCLUSION

The instrument panel contour angle (α), measured relative to the vertical, plays a pivotal role in managing upper leg injuries during collisions. The present study indicates that an increase in this angle (α) effectively reduces knee shear displacement, thereby lowering the risk of injury. This is especially important in cab-over-engine vehicles because there are no energy-absorbing structures in front of the cabin, thus the instrument panel's capacity to control impact forces is even more important. The design and stiffness of the instrument panel are instrumental in dissipating collision energy and thus reducing stress on the upper legs. By optimising the contour angle and stiffness properties, manufacturers can enhance the energy absorption characteristics of the instrument panel, significantly improving occupant protection.

VI. REFERENCES

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